V and I Photometry of Bright Giants in the Central Regions of NGC147

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ABSTRACT

Deep V and I CCD images with sub-arcsec spatial resolution are used to investigate the stellar content of the central regions of the Local Group dwarf elliptical galaxy NGC147. Red giant branch (RGB) stars are resolved over the entire field, and the RGB-tip occurs at $I \sim 20.5$, suggesting that the distance modulus is 24.3. A comparison with globular cluster sequences indicates that the center of NGC147 is moderately metal-poor, with $\overline{[Fe/H]} \sim -1$. This is not significantly different from what was found in the outer regions of the galaxy by Mould, Kristian & Da Costa (1983, ApJ, 270, 471). Moreover, the width of the $V - I$ color distribution at $I = 21.0$ indicates that a spread in metallicity is present, with $\sigma_{[Fe/H]} \sim \pm 0.3$. There is no evidence of a component more metal-poor than [Fe/H] ~ -1.3. A small population of moderately bright asymptotic giant branch (AGB) stars has also been detected, and the AGB-tip occurs near $M_{bol} \sim -5.0$, indicating that an intermediate-age population is present. It is estimated that the intermediate-age population contributes $\sim 2 - 3\%$ of the V light from NGC147.

1. INTRODUCTION

Because they are relatively close, Local Group galaxies provide unique templates for interpreting more distant, unresolved, objects. Studies of nearby dwarf galaxies are of particular interest, as it has recently been suggested that low mass systems at intermediate redshifts may have experienced large bursts of star formation (e.g. Broadhurst, Ellis, & Shanks 1988; Eales 1993; Colless et al. 1993). One signature of large-scale star formation at moderate redshifts will be a population of intermediate-age stars, and the spatial distribution of such a component may influence present-day morphologies. Indeed, Babul & Reese (1992) suggest that non-nucleated dwarf elliptical (dE) and nucleated dwarf elliptical (dE,n) systems may have experienced systematically different star-forming histories. Comparative studies of the stellar contents of nearby nucleated and non-nucleated dwarf ellipticals provide a direct means of testing predictions of this nature.

A potential problem with using Local Group galaxies as models for more distant systems is that many are companions to the Galaxy or M31, so that tidal interactions may have influenced their evolution. However, early-type dwarf galaxies tend to cluster around more massive systems (e.g. Vader & Sandage 1991), suggesting that the companions to M31 and the Galaxy may actually provide more 'typical' templates for dwarf galaxy evolution than isolated members of the Local Group. The M31 satellite system provides a number of lucrative targets for detailed investigation, which cover a range of morphological types. Three of the satellites of M31 are low surface-brightness

dwarf ellipticals: NGC147, NGC185, and NGC205. NGC205 is type dE,n while NGC147 and NGC185 are type dE (e.g. Kent 1987). These galaxies have conspicuously different young stellar contents. Early photographic studies of NGC185 and NGC205 by Baade (1951) and Hodge (1963; 1973) revealed centrally-concentrated populations of blue stars. Moreover, NGC185 and NGC205 both contain dust clouds (Hodge 1963, 1973), suggesting that star-forming activity may not have ceased. On the other hand, NGC147 does not contain massive young stars, and there is no evidence for dust absorption (Hodge 1976), suggesting that massive stars will not form in the immediate future.

Although relatively easy to detect, massive stars probe only the most recent histories of galaxies. Observations which sample longer time spans, preferably extending into intermediate epochs, will provide a more thorough means of comparing the evolutionary histories of dwarf galaxies. Deep red and near-infrared images are particularly effective for detecting bright AGB stars, and observations of this nature have revealed intermediate-age populations in NGC185 and NGC205 (Richer, Crabtree & Pritchet 1984, Davidge 1992, Lee, Freedman, & Madore 1993). At present, there is no evidence to suggest that an intermediate age population is present in NGC147. Mould, Kristian, & Da Costa (1983) obtained deep V and I images of a field 5 arcmin from the galaxy center and found a well-defined red giant branch (RGB) with a color appropriate for [Fe/H] ~ -1.2. Bright AGB stars were abscent, and a subsequent study of star clusters by Da Costa & Mould (1988) also failed

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to detect an intermediate-age population.

If present in NGC147, luminous AGB stars should be most easily detected in the central regions of the galaxy, where the stellar density is greatest, and the chances of detecting stars during short-lived phases of their evolution is largest. In an effort to search for luminous AGB stars, a series of deep V and I images were obtained of the center of NGC147, and the results of this survey are reported here. The data and their reduction are discussed in Section 2. The $(I, V - I)$ color-magnitude diagram (CMD) and I luminosity function are presented in Section 3, and these reveal a well-defined RGB, with a modest population of AGB stars extending up to $M_{bol} \sim -5.0$. In Section 4 the $V - I$ color distribution at $I \sim 21.0 \pm 0.25$ is examined in an effort to determine the mean metallicity and metallicity dispersion. A brief summary and discussion of the results follows in Section 5.

2. OBSERVATIONS AND REDUCTIONS

The data were recorded during the night of UT January 1/2 1992 using the HRCAM imager (McClure et al. 1989), mounted at the prime focus of the 3.6 metre Canada-France-Hawaii Telescope (CFHT). The detector was SAIC1, a thick Ford-Aerospace type CCD with 18μm square pixels in a 1024 x 1024 format. The spatial scale produced by this instrument/detector combination is 0.13 arcsec/pixel, so that each image covered ~ 5 square arcmin.

A field centered near right ascension $00^h30^m32^s$ and declination $+48^o13'37"$ (epoch 1950) was observed. Six 300 sec exposures were recorded through a Kron-Cousins I filter, while ten 300 sec exposures were recorded in V. The

telescope pointing experienced a ∼ 25 arcsec jump mid-way through the observing sequence, which went undetected at the telescope. Hence, the field coverage of the final combined images is smaller than would otherwise have been the case (∼ 2.5 square arcmin). The mean seeing, derived from bright stars in the final combined images, was 0.8 arcsec FWHM in both filters.

The data reduction followed standard lines. A median bias frame was subtracted from the raw exposures, and the results were divided by dome flats appropriate for each filter. Corrections were not made for detector dark current due to the relatively short exposure times. The flat-fielded images were aligned, co-added, and trimmed to the area common to all exposures. The final I image is shown in Figure 1.

3. PHOTOMETRY

3.1 Stellar Brightnesses

Stellar brightnesses were measured with the PSF-fitting routine ALLSTAR (Stetson & Harris 1988), which is part of the DAOPHOT (Stetson 1987) photometry package. Standard stars in the globular cluster NGC2419 (Christian et al. 1985) were used to calibrate the photometry. Standards were observed only once during the night, so mean extinction coefficients, derived from previous runs, were adopted for calibration purposes. The uncertainties in the photometric zeropoints are ±0.02 magnitudes.

Artificial star experiments were run to determine completeness fractions and assess systematic effects in the photometry. The results depend on crowding, the extent of which changes across the field, being greatest near

the center of the galaxy. To partially compensate for spatial variations in stellar density, the field was divided into three regions, centered on the globular cluster Hodge 1, which lies close to the photometric center of NGC147 (Hodge 1976). The boundaries of these regions were selected to produce equal integrated brightnesses; hence, to first order the regions should contain comparable numbers of stars. Region 1 covers a 27 arcsec radius centered on Hodge 1, while Region 2 spans the interval from 27 to 43 arcsec. Region 3 covers the remaining parts of the image. The total areas covered on the final images are 0.45, 0.55, and 1.53 square arcmin, respectively. The data are 50% complete in Regions 1 , 2, and 3 when $V = 22.6, 22.9$, and 23.1, and $I = 22.0, 22.2$, and 22.5.

Hodge (1976) measured the brightness of the cluster Hodge 1 photoelectrically, and found that $V = 17.66$ within a 14 arcsec aperture. For comparison, the current data indicate that $V = 17.57$ and $V - I = 1.50$ within the same aperture. These values may not be representative of the cluster, as the CCD data reveal that the light profile of Hodge 1 declines at a relatively steep rate, such that at a 2 arcsec radius the mean I surface brightness is comparable to that of the surrounding galaxy. Indeed, $V - I$ becomes steadily bluer as aperture size decreases, such that with a 2 arcsec aperture $(V - I) \sim 1.15$, while $V \sim 18.68$. Adopting $E(B - V) \sim 0.18$ (Burstein & Heiles 1984), a value which will be used throughout this paper, then the reddening curve of Dean, Warren, & Cousins (1978) implies that $E(V - I) = 0.23$, so that $(V - I)_0 = 0.92$ within the 2 arcsec aperture. Da Costa & Mould (1988)

studied the spectroscopic properties of Hodge 1, and found that the W(K) + W(M) index, where W(K) and W(M) measure the strengths of Ca K and red metallic features, respectively, is similar to M13, for which $(V - I)_0 \sim 0.8$ (Reed, Hesser, & Shawl 1988). Hence, there is broad agreement between the spectroscopic and photometric properties of Hodge 1.

3.2 The CMD's and Luminosity Functions

The $(I, V - I)$ diagram of the entire field is shown in Figure 2, and the red giant branch (RGB) is clearly visible. A population of moderately bright red stars, which are evolving on the AGB, is also apparent, and the upper envelope of this sequence occurs near $I \sim 19.8$. The small number of stars brighter than $I \sim 19.0$ in Figure 2 are probably foreground objects. Evidence for this comes from the Galactic star count models of Ratnatunga & Bahcall (1985), who predict that ~ 4 stars brighter than $V = 19$ should be detected in the current field. For comparison, 6 stars brighter than $V = 19$ were detected, in reasonable agreement with the model star counts.

The $(I, V - I)$ CMD's for Regions 1, 2, and 3 are compared in Figure 3. Region 1 is more crowded than Region 3, so it is not surprising that more stars were detected in the latter area than the former. If the central regions of NGC147 are dominated by an old population, as appears to be the case (Section 5), then the mean metallicity can be determined by comparison with Galactic globular cluster sequences. The loci of the clusters NGC7078 and 47 Tuc ([Fe/H] ~ -2.2 and -0.7; Zinn & West 1984), as tabulated by Da Costa & Armandroff (1990), are compared with the NGC147 observations in

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Figure 3. A distance modulus of 24.3, which places the RGB-tip at $I \sim 20.5$ (see below) if $E(V-I) \sim 0.23$, has been assumed. It is evident that the majority of stars in all three regions fall between the NGC7078 and 47 Tuc loci, although there is a small spray of stars which fall redward of the 47 Tuc sequence. The nature of these objects will be discussed further in Section 4.

The I luminosity function can be used to determine the brightness of the RGB-tip. A large dataset is required for this task, as the RGB-tip may be a relatively small feature, superimposed on a sloping luminosity function. In order to use the maximum possible number of stars from the current dataset, a composite I luminosity function for all three regions was constructed using all stars detected in I, and the result is shown in Figure 4. In this Figure N is the number of stars per 0.25 magnitude per square arcmin. A discontinuity is apparent near $I \sim 20.5$, which is due to the RGB-tip. For comparison, Mould et al. (1983) concluded that the RGB-tip occurs at $I \sim 20.4$ in NGC147.

The absence of luminous resolved early-type stars suggests that, unlike NGC205 and NGC185, there has not been recent star formation in NGC147. However, the brightness of the AGB-tip suggests that star formation did occur during intermediate epochs. The brightness of the AGB-tip is best determined from a bolometric, rather than monochromatic, luminosity function, as the AGB sequence becomes degenerate with color at high luminosities. The brightest AGB stars in an old, moderately metal-poor stellar system, such as the globular cluster 47 Tuc, have $M_{bol} \sim -4.5$ (Frogel, Persson, & Cohen 1981). Consequently, if the AGB-tip in NGC147 is brighter than

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this then it is likely that an intermediate-age component is present. A bolometric AGB luminosity function for NGC147 has been computed using the procedure described by Reid & Mould (1984), with bolometric corrections derived from Equation 1 of Bessell & Wood (1984). The result, corrected for completeness, is shown in Figure 5, where N is the number of stars per square arcmin per 0.25 magnitude interval. A distance modulus $\mu \sim 24.3$ has been assumed. The brightest stars have $M_{bol} \sim -5.0$, indicating that an intermediate age component is present.

4. THE RGB COLOR DISTRIBUTION

The color distribution of RGB stars can be used to determine the mean metallicity and metallicity dispersion near the center of NGC147. The distribution of $V - I$ colors for stars with $I \sim 21.0 \pm 0.25$ in Regions 1, 2, and 3 are compared in Figure 6. These distributions were computed using a 0.2 magnitude bin in $V - I$, and have been corrected for incompleteness. The mean colors in the three zones are very similar, with $\overline{V - I} \sim 2.0$. Moreover, in all three cases there is a steep blue envelope at $V - I \sim 1.4$, and a red tail which extends beyond $V - I \sim 2.0$. The Region 1 and 2 distributions show a two-peaked profile not apparent in Region 3; however, a Kolmogoroff-Smirnoff test indicates that the three distributions are not significantly different.

The composite color distribution for all three fields is shown in Figure 7. A series of model color distributions, broadened with error functions determined from the artificial star experiments, were computed using the globular cluster loci tabulated by Da Costa & Armandroff (1990), and the results for

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NGC1851 ([Fe/H] ~ -1.3; Zinn & West 1984) and 47 Tuc are compared with the observations in Figure 7. No attempt was made to produce optimum fits with the observations; rather, the models were simply scaled so that their peaks matched the observed color distributions. It is apparent that (1) a range of metallicities is required to match the color distribution; (2) the majority of stars have [Fe/H] between that of NGC1851 and 47 Tuc, so that $\sigma_{[Fe/H]} \sim \pm 0.3$, and $\overline{[Fe/H]} \sim -1$; (3) there is no evidence for a very metal-poor (ie. [Fe/H] ~ -2) population; and (4) the spray of stars falling redward of the 47 Tuc sequence in Figure 3 is actually the gaussian tail of a moderately metal-poor component. The mean metallicity found here is consistent with that derived by Mould et al. (1983) at larger radii. Mould et al. (1983) also found evidence for a metallicity dispersion, as did Saha, Hoessel, & Mossman (1990), who studied the period distribution of RR Lyrae variables.

5. SUMMARY AND DISCUSSION

The photometry presented in this paper indicates that the central regions of NGC147 are moderately metal-poor, and contain stars spanning metallicities in the range $-1.3 \leq [Fe/H] \leq -0.7$. Moreover, a small population of stars which formed at intermediate epochs is also present. The implications of these results are briefly discussed below.

The $I, V - I$ CMD in Figure 2 is morphologically similar to that constructed by Mould et al. (1983) for a field 5 arcmin from the center of NGC147, and the current results indicate that mean metallicity does not

vary significantly across the face of the galaxy. Consequently, if a metallicity gradient is present in NGC147 then it must be very shallow. This is qualitatively consistent with non-conservative galaxy formation models, which predict that supernovae-driven winds eject star-forming material from low mass systems early in their evolution, halting chemical enrichment and preventing dissipative collapse (e.g. Carlberg 1984; Dekel & Silk 1986). The seeming absence of a very low metallicity (ie. [Fe/H] ~ -2) component suggests that the main body of NGC147 may have experienced very rapid initial chemical enrichment or formed from previously enriched material. However, NGC147 is not completely devoid of metal-poor stars, as Da Costa & Mould (1988) found that the clusters Hodge 1 and Hodge 3 have [Fe/H] ~ -2.0.

The age of the intermediate age component in NGC147 can be estimated from the brightness of the AGB-tip. Using the calibration of Mould & Aaronson (1988), $M_{bol} \sim -5$ corresponds to an age of ~ 5 Gyr. The detection of intermediate-age stars in the central regions of NGC147 is of interest as Mould et al. (1983) failed to detect bright AGB stars 5 arcmin from the galaxy center. However, this may be a consequence of the low density of these objects at large radii. This can be demonstrated by comparing the mean surface brightnesses in the central and Mould et al. (1983) fields. The luminosity profile measured by Kent (1987) indicates that the mean surface brightness in the Mould et al. field is $\mu_g \sim 26$ mag/arcsec^2, compared with $\mu_g \sim 21.7$ mag/arcsec^2 near the galaxy center. Therefore, the stellar density in the Mould et al. field should be ~ 0.02 times that near the center. After

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correcting for differences in field size, Mould et al. (1983) should have detected one tenth the number of bright AGB stars found in the current study *if the relative densities of old and intermediate-age stars were the same as in the galaxy center*. Roughly 50 stars brighter than the RGB-tip have been detected in the current study, so ~ 5 would be expected in the Mould et al. (1983) field. Such a small number of stars may be difficult to detect given the foreground contamination towards NGC147 (eg. Figure 9 of Mould et al. 1983).

The contribution that the intermediate-age component makes to the integrated light from NGC147 can be estimated from the AGB luminosity function. Frogel, Mould, & Blanco (1990) computed the fractional contribution that AGB stars make to total cluster luminosities. Unfortunately, this calibration uses AGB stars as faint as $M_{bol} \sim -3.6$, and so is unsuitable for the current study, as NGC147 is likely not coeval, and AGB stars fainter than $M_{bol} \sim -4.5$ could belong to older populations. Consequently, a revised calibration was derived from the Frogel et al. (1990) dataset using only AGB stars with $M_{bol} \leq -4.5$. Moreover, the sample was restricted to clusters of SWB (Searle, Wilkinson, & Bagnuolo 1980) types 5.5 and 6, as these have ages comparable to the intermediate-age population in NGC147 (e.g. Table 3 of Frogel et al. 1990). This exercise revealed that AGB stars brighter than $M_{bol} \sim -4.5$ contribute 0.22 ± 0.05 of the total luminosity from SWB types 5.5 and 6 clusters. A direct integration of the AGB luminosity functions from Regions 1, 2, and 3 reveals that the total luminosity of bright AGB stars is

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$M_{bol} \sim -6.6$, so that the total luminosity of the intermediate-age population near the center of NGC147 is $M_{bol} \sim -8.2$. If the spectral-energy distribution of this population is similar to that of a late G or early K giant then the bolometric correction will be ~ -0.1, so that $M_V \sim -8.3$. The integrated brightness of the current field is $M_V \sim -12.3$. Hence, the intermediate-age component contributes only $\sim 2 - 3\%$ of the total light output in V near the galaxy center.

REFERENCES

Baade, W. 1951, Pub. Univ. Michigan Obs., 10, 7

Babul, A., & Rees, M. J. 1992, MNRAS, 255, 346

Bessell, M. S., & Wood, P. R. 1984, PASP, 96, 247

Broadhurst, T. J., Ellis, R. S., & Shanks, T. 1988, MNRAS, 235, 827

Burstein, D., & Heiles, C. 1984, ApJS, 54, 33

Carlberg, R. G. 1984, ApJ, 286, 403

Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S.,
    Mould, J. R., & Siegel, M. 1985, PASP, 97, 363

Colless, M., Ellis, R. S., Broadhurst, T. J., Taylor, K., & Peterson,
    B. A. 1993, MNRAS, 261, 19

Da Costa, G. S., & Armandroff, T. E. 1990, AJ, 100, 162

Da Costa, G. S., & Mould, J. R. 1988, ApJ, 334, 159

Davidge, T. J. 1992, ApJ, 397, 457

Dean, J. F., Warren, P. R., & Cousins, A. W. J. 1978, MNRAS, 183, 569

Dekel, A., & Silk, J. 1986, ApJ, 303, 39

Eales, S. 1993, ApJ, 404, 51

Frogel, J. A., Mould, J., & Blanco, V. M. 1990, ApJ, 352, 96

Frogel, J. A., Persson, S. E., & Cohen, J. G. 1981, ApJ, 246, 842

Hodge, P. W. 1963, AJ, 68, 691

Hodge, P. W. 1973, ApJ, 182, 671

Hodge, P. W. 1976, AJ, 81, 25

Kent, S. M. 1987, AJ, 94, 306

Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, AJ, 106, 964

McClure, R. D., Grundmann, W. A., Rambold, W. N., Fletcher, J. M., Richardson, E. H., Stilburn, J. R., Racine, R., Christian, C. A., & Waddell, P. 1989, PASP, 101, 1156

Mould, J. R., & Da Costa, G. S. 1988, in Progress and Opportunities in Southern Hemisphere Optical Astronomy, ed. V. M. Blanco & M. M. Phillips (ASP: San Francisco), 197

Mould, J. R., Kristian, J., & Da Costa, G. S. 1983, ApJ, 270, 471

Ratnatunga, K. U., & Bahcall, J. N. 1985, ApJS, 59, 63

Reed, E. C., Hesser, J. E., & Shawl, S. J. 1988, PASP, 100, 545

Reid, N., & Mould, J. 1984, ApJ, 284, 98

Richer, H. B., Crabtree, D. R., & Pritchet, C. J. 1984, ApJ, 287, 138

Saha, A., Hoessel, J. G., & Mossman, A. E. 1990, AJ, 100, 108

Searle, L., Wilkinson, A., & Bagnuolo, W. G. 1980, ApJ, 239, 803

Stetson, P. B. 1987, PASP, 99, 191

Stetson, P. B., & Harris, W. E. 1988, AJ, 96, 909

Vader, J. P., & Sandage, A. 1991, ApJL, 379, L1

Zinn, R., & West, M. J. 1984, ApJS, 55, 45

Zinnecker, H., & Cannon, R. D. 1985, in Star Forming Dawrf Galaxies and Related Objects, ed. D. Kunth, T. X. Thuan, & J. Tran Tranh Van (Gif-Sur-Yvettes:Editions Frontieres), 155

FIGURE CAPTIONS

FIG. 1. The final I image of the NGC147 field.

FIG. 2. The $(I, V - I)$ CMD of the entire field.

FIG. 3. The $(I, V - I)$ CMD's for, from left to right, Regions 1, 2, and 3. The solid lines are the loci of the clusters NGC7078 and 47 Tuc from Da Costa & Armandroff (1990). The placement of the cluster loci assume $\mu \sim 24.3$ and $E(B - V) \sim 0.17$.

FIG. 4. The completeness-corrected I luminosity function for all three regions derived from all stars detected in I. Note the discontinuity near $I \sim 20.5$. N is the number of stars per 0.25 magnitude interval per square arcmin. The error bars reflect counting statistics.

FIG. 5. The completeness-corrected bolometric AGB luminosity function for NGC147. N is the number of stars per 0.25 magnitude interval per square arcmin. The error bars reflect counting statistics.

FIG. 6. The $(V - I)$ color distributions at $I = 21 \pm 0.25$ for, from top to bottom, Regions 1, 2, and 3. n is the number of stars per 0.2 magnitude interval normalised to the total number of stars detected in each region. The curves have been corrected for incompleteness.

FIG. 7. The composite $V - I$ color distribution at $I \sim 21.0 \pm 0.25$ for all three regions. Also shown are the color distributions expected for single-metallicity populations corresponding to the globular clusters NGC1851 (dashed line)

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and 47 Tuc (dotted-dashed line). The model distributions have been scaled to roughly match the observed color distribution near the peak model distribution.